All Electronic Phase-Retrieval Measurement of Femtosecond Optical Waveform

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Outline

- Characterization of femtosecond optical waveform by nonlinear wave mixing
  1. autocorrelator
  2. frequency resolved optical gating

- All electronic phase retrieval measurement using nonlinear detectors
  1. experimental setup
  2. waveform reconstruction algorithm

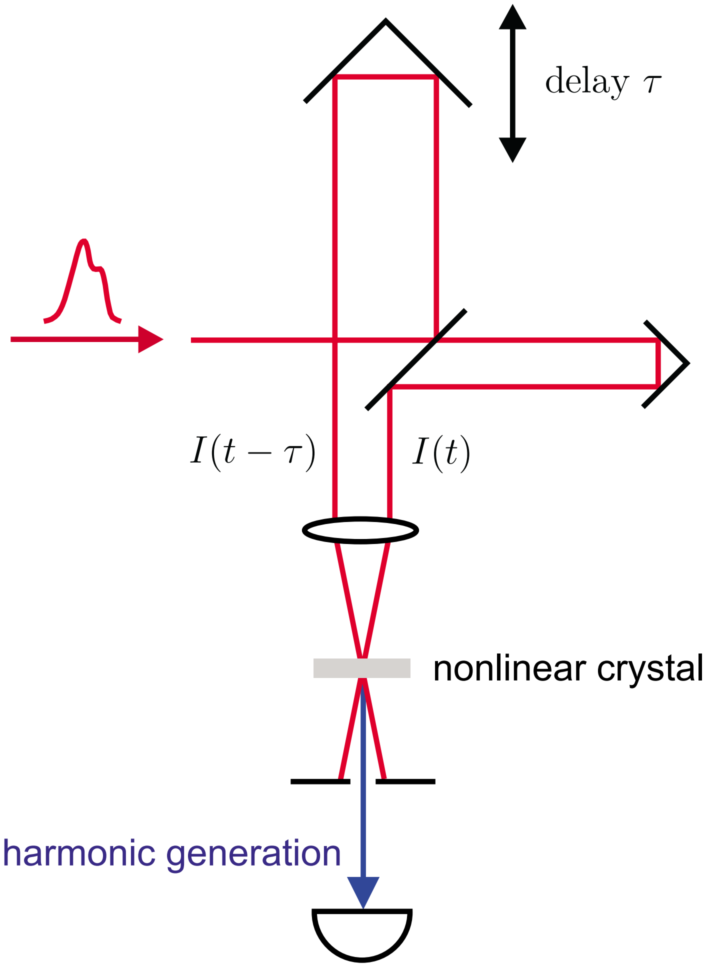
- Potential applications
  1. ultrafast spectroscopy
  2. beam diagnosis for accelerator

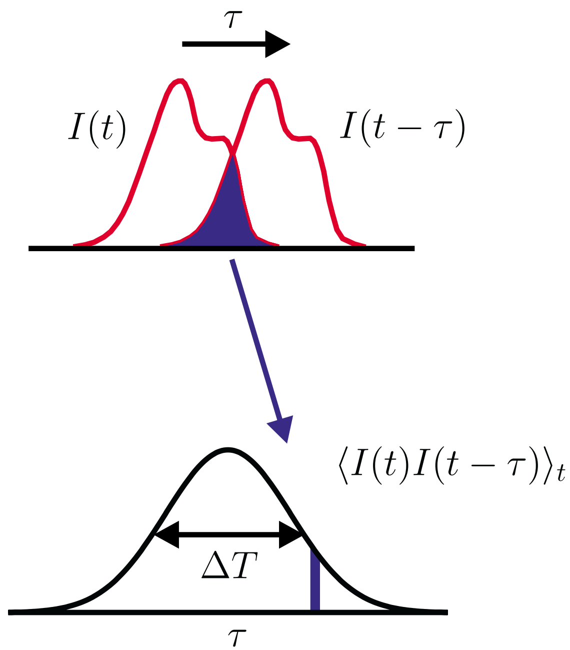
Characterization of femtosecond optical waveform by nonlinear wave mixing

1. autocorrelator

2. frequency resolved optical gating

Intensity autocorrelator

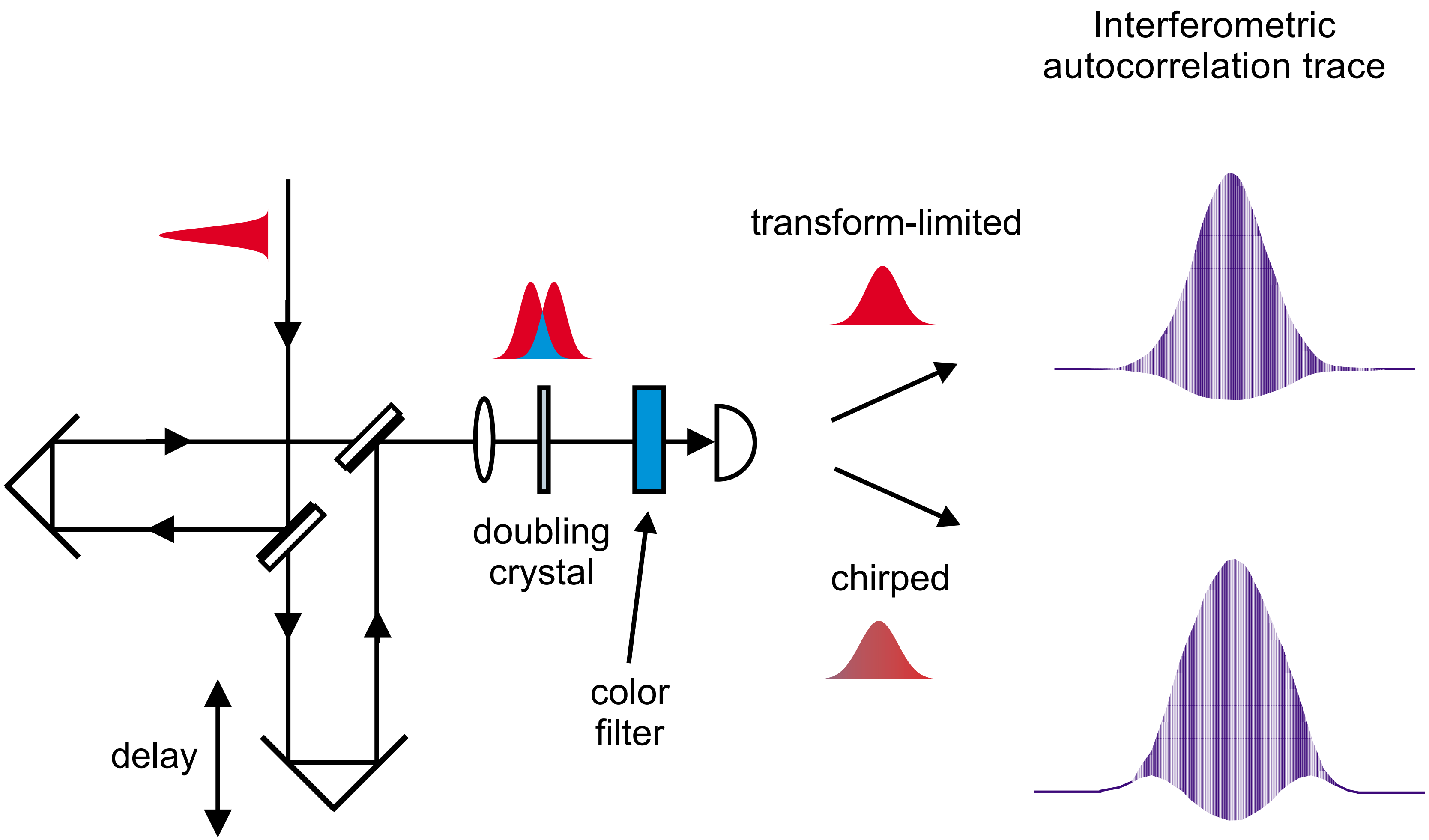




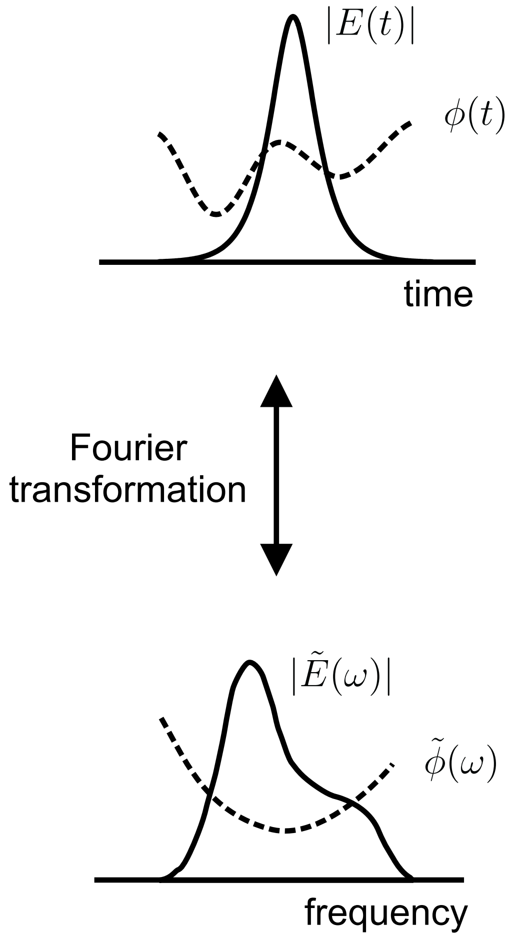
autocorrelation trace

$$\text{pulse duration} = 0.648\ \Delta T\ (\text{sech}^2\ \text{shape})$$

Interferometric autocorrelation



Characterization of femtosecond pulses



$$E(t) = |E(t)|e^{i\phi(t)}$$

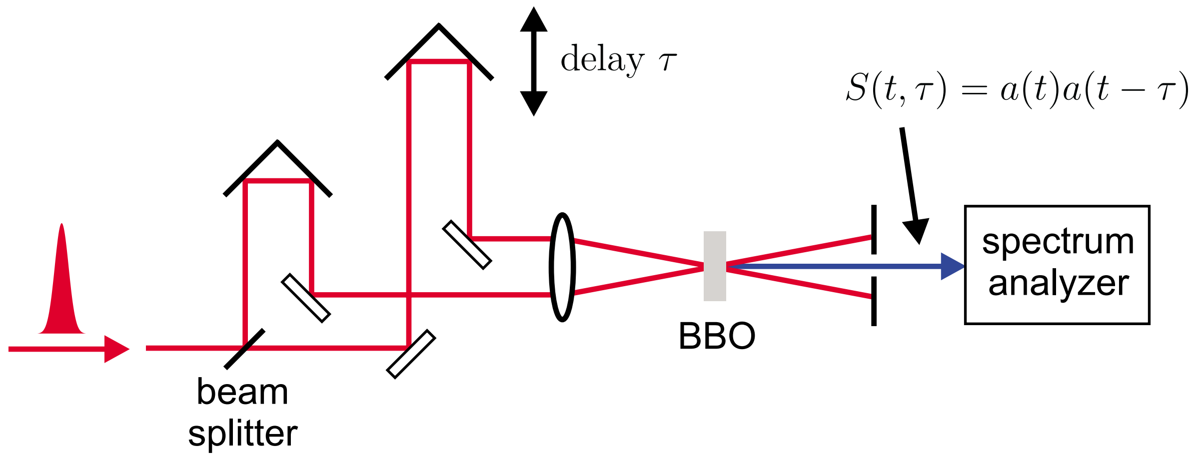
Hard to analyze in femtosecond time scale.

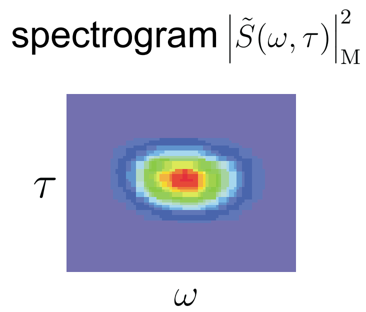
?

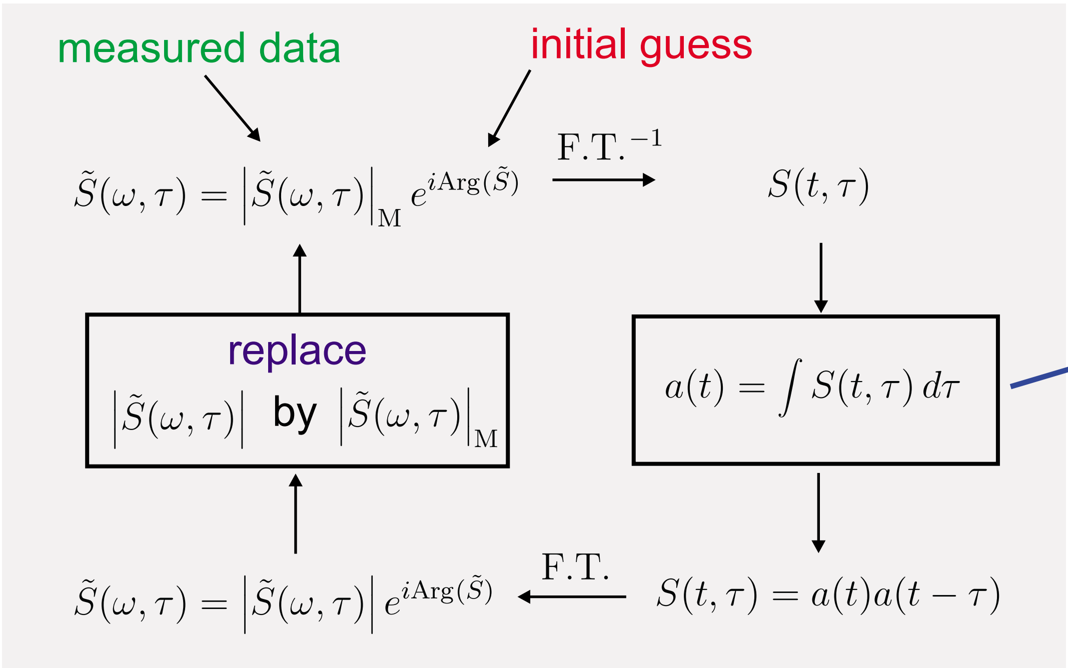
$$\tilde{E}(\omega) = \underline{|\tilde{E}(\omega)|}e^{i\tilde{\phi}(\omega)}$$

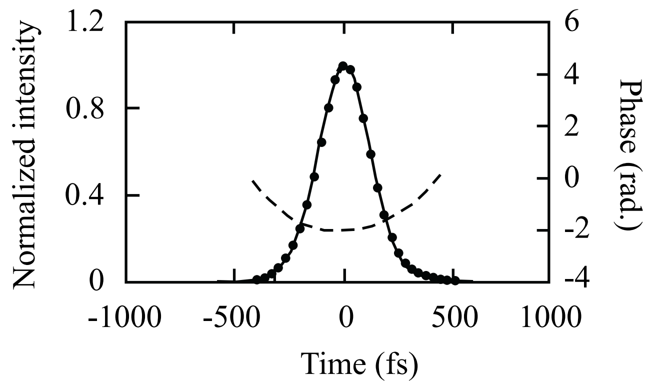
Easy to measure by spectrum analyzer.

Frequency-resolved optical gating









D. J. Kane and R. Trebino, *Opt. Lett.* **18**, 823 (1993).

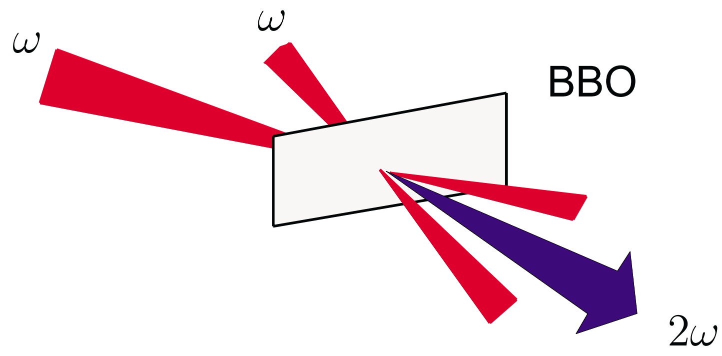
All electronic phase retrieval measurement using nonlinear detectors

1. two-photon interferometry

2. waveform reconstruction algorithm

Limitations of optical nonlinear wave mixing

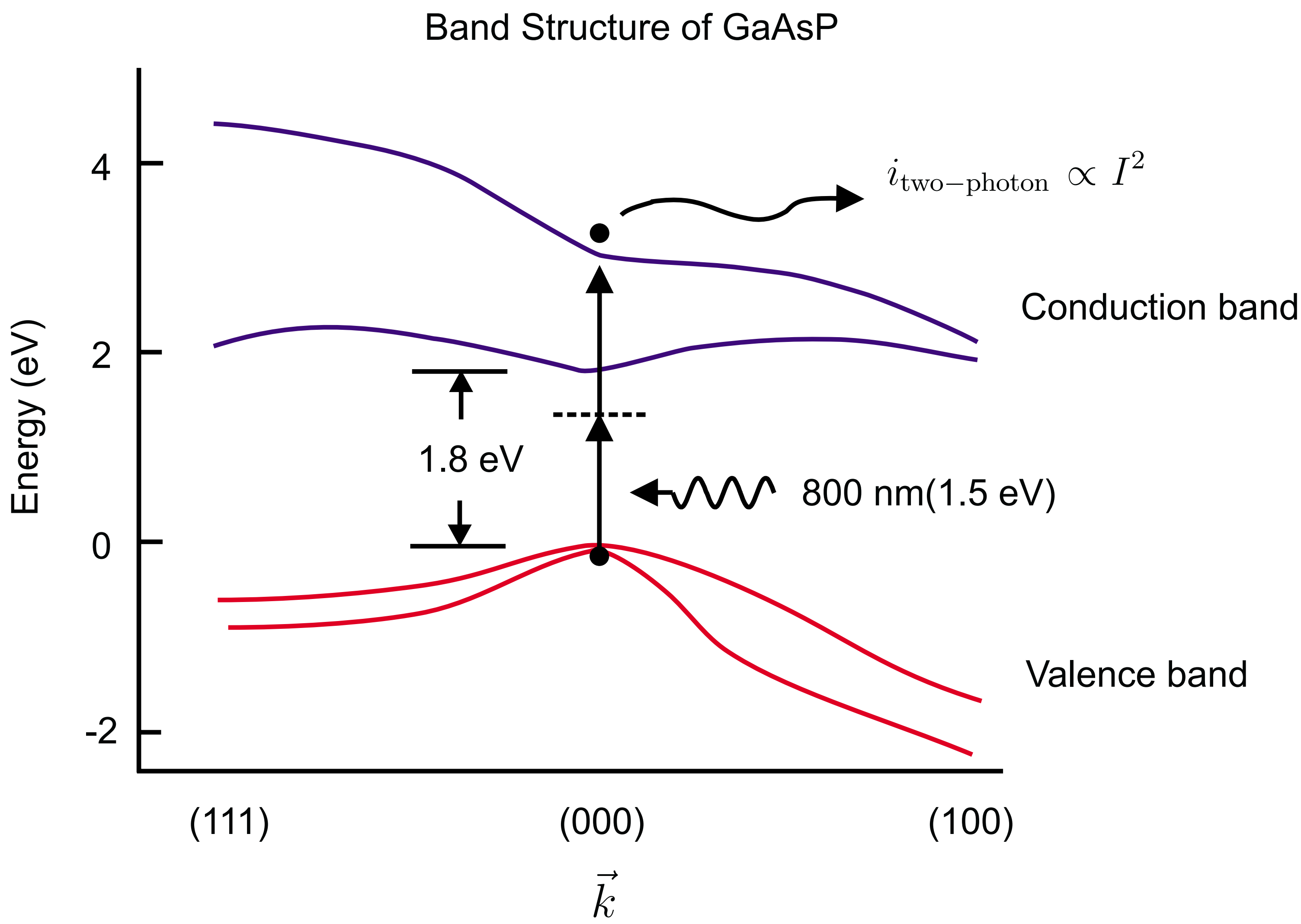
nonlinear wave mixing



Limitations:

1. Dispersion: causes pulse broadening and walk-off.
2. Phase-matching bandwidth: requires thin crystal.
3. Inefficient process: limits sensitivity.

Two-photon induced photocurrent in semiconductor



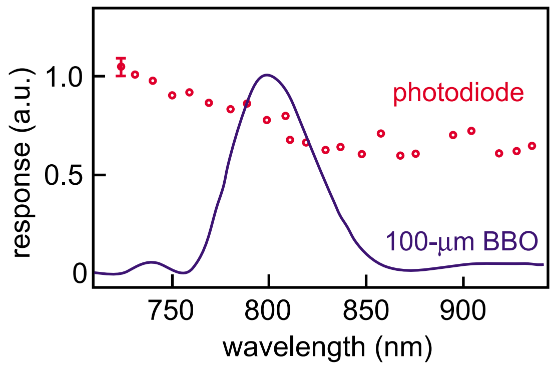
Advantages of using two-photon photodiodes for nonlinear measurements

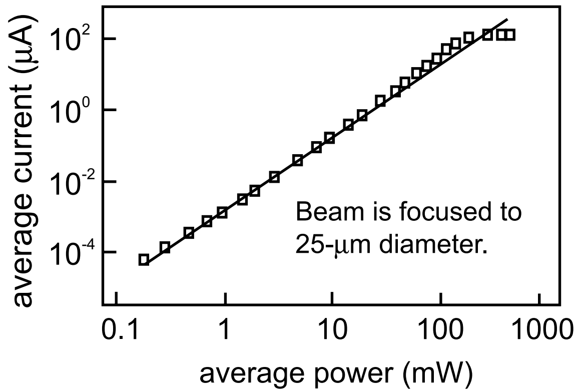
1. Bandwidth: nearly uniform up to 200 nm.

2. Sensitivity: up to 1.42 nA/mW^2, comparable to 100-μm BBO + photomultiplier.

3. Simplicity: easy alignment and no phase-matching requirements.

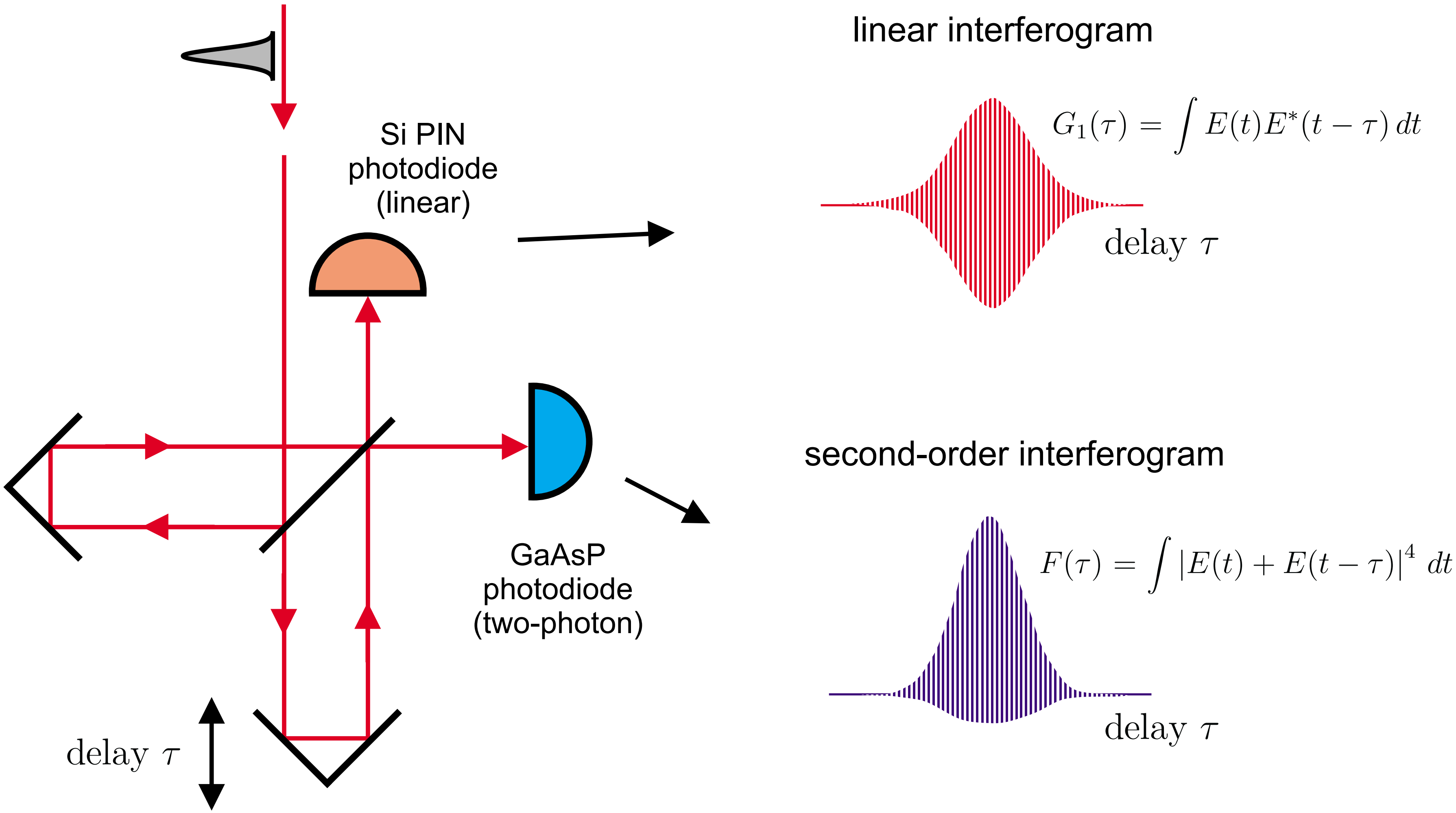
4. Low cost: less than US$100.



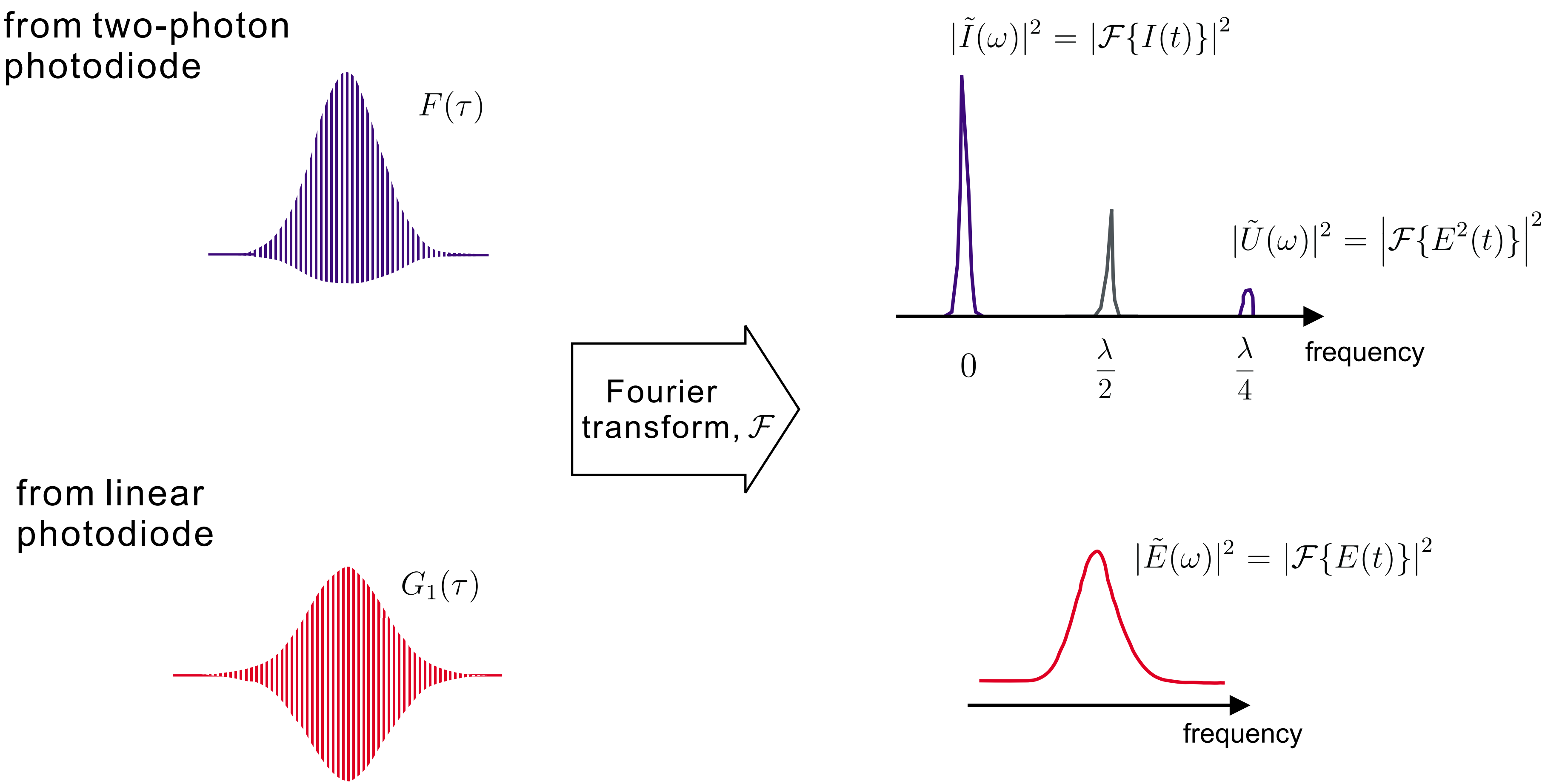


Ref: J.-K. Ranka and *et al.*, *Optics Letters* **22**, pp.1344, (1997).

Two-photon photodiode-based phase-retrieval autocorrelator



Spectral components of the autocorrelation function



Unique phase retrieval from measured spectrums

$$|\tilde{E}(\omega)|^2 = |\mathcal{F}\{E(t)\}|^2$$

$$|\tilde{I}(\omega)|^2 = |\mathcal{F}\{I(t)\}|^2$$

$$|\tilde{U}(\omega)|^2 = \left|\mathcal{F}\{E^2(t)\}\right|^2$$

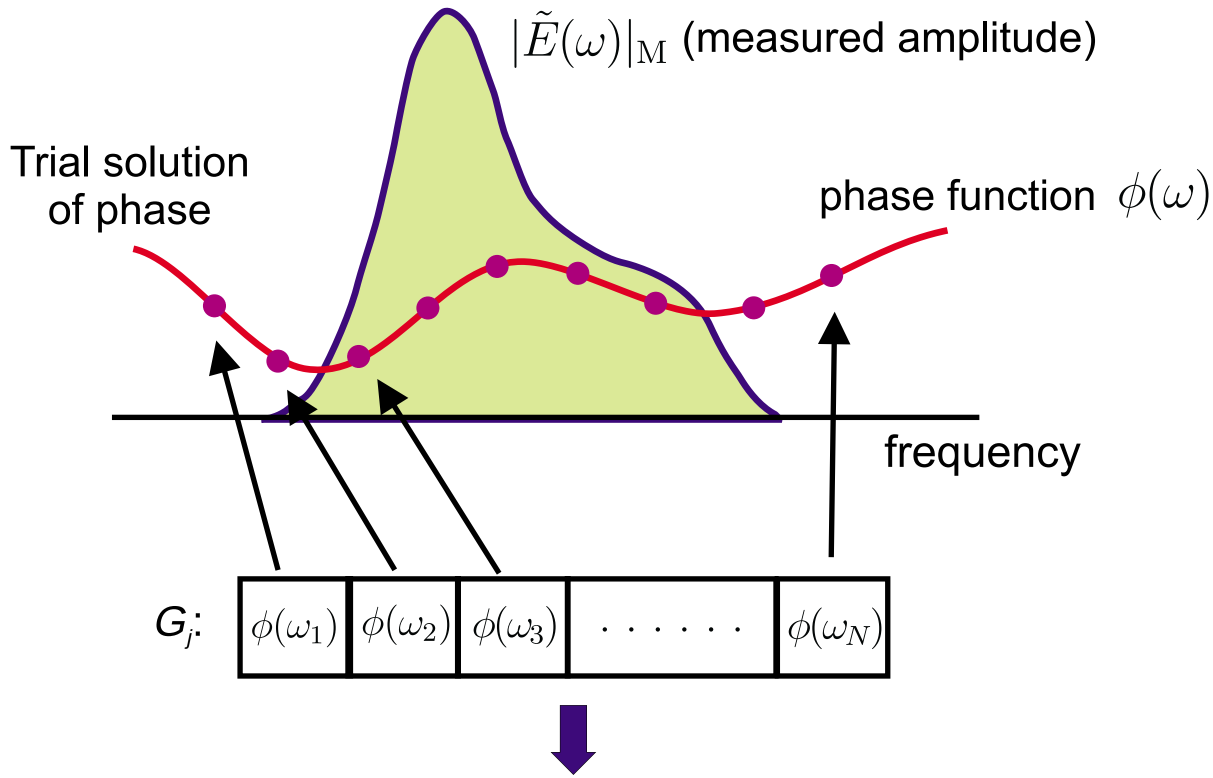
→ uniquely determine the waveform

Ref. : K. Naganuma, K. Mogi, and H. Yamada, IEEE *J. Quantum Electron.* **25,** 1225 (1989).

Genetic Algorithm

1. crossover
2. mutation
3. selection

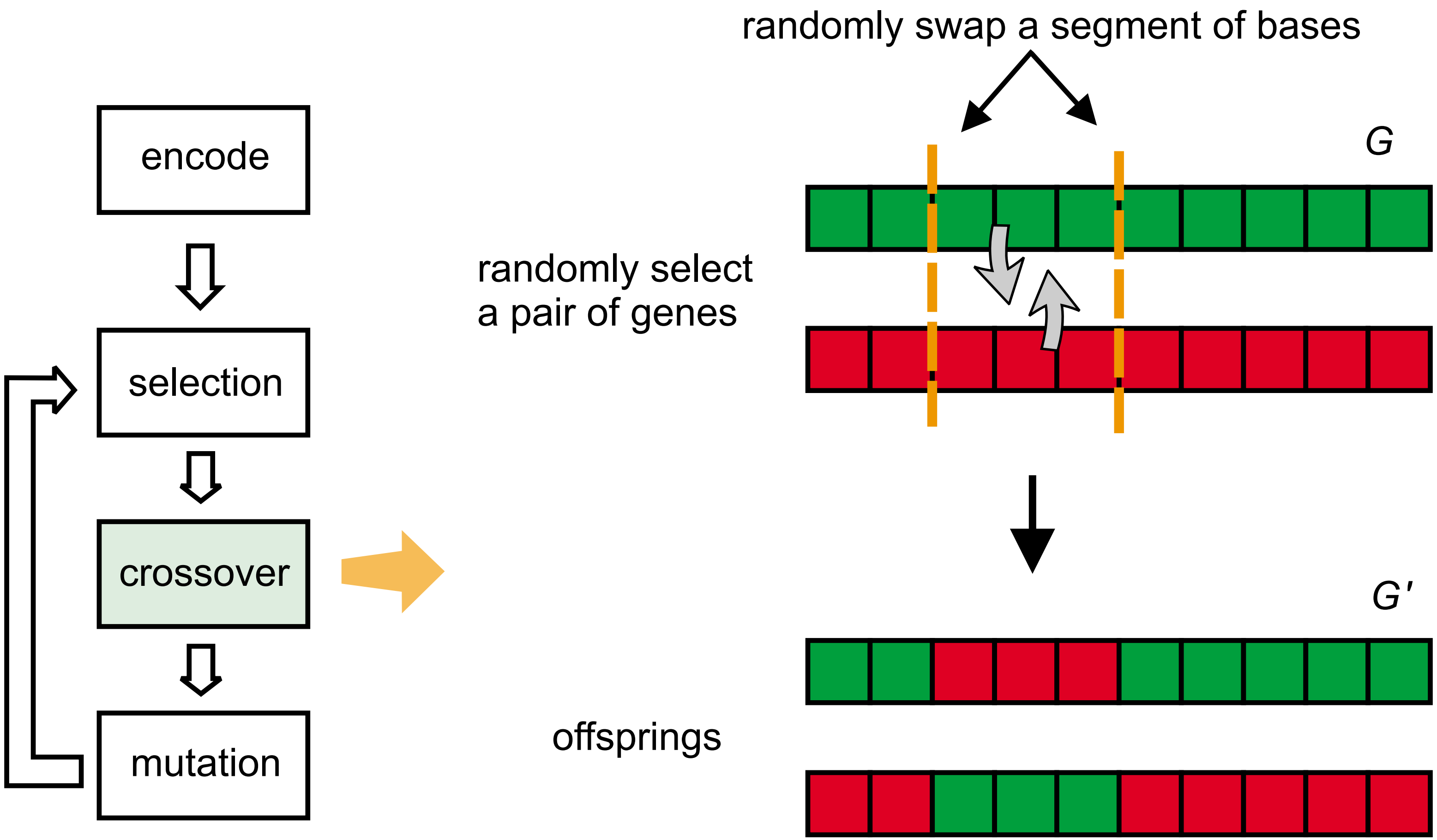
Representing the phase function by genes



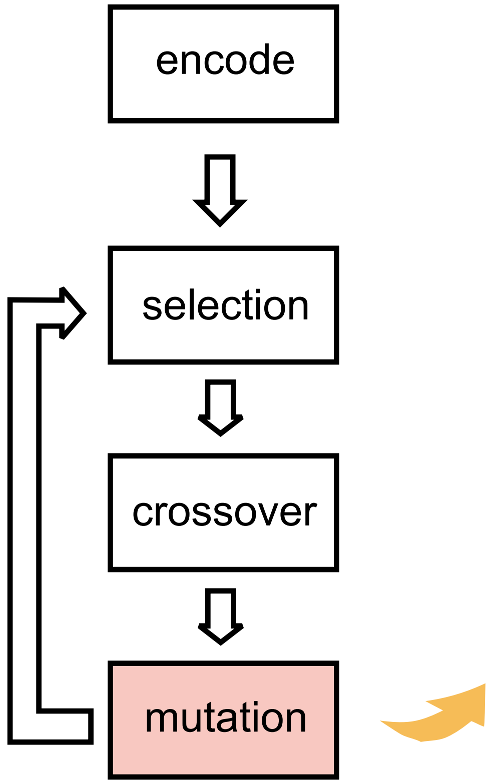
$$\tilde{E}(\omega) = |\tilde{E}(\omega)|_{\mathrm{M}} \cdot \exp[i\phi(\omega)]$$

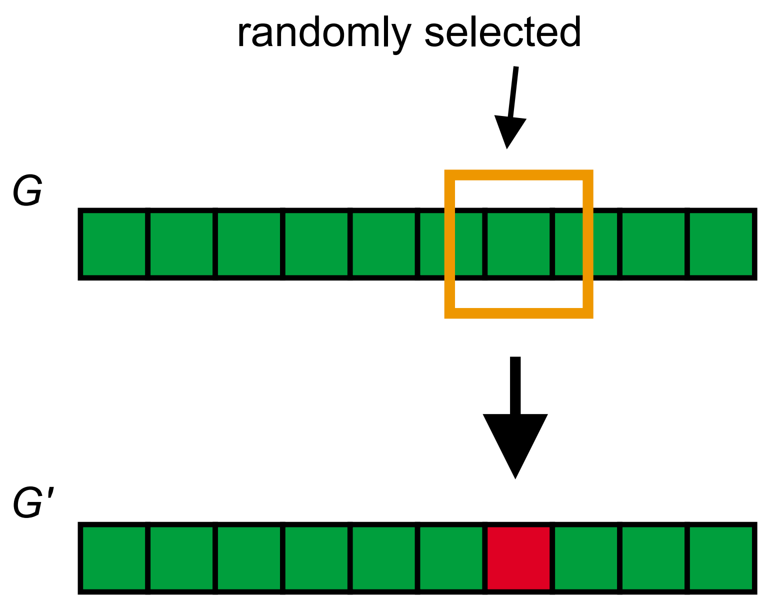
$$E(t) = \mathcal{F}^{-1}\{\tilde{E}(\omega)\}$$

Basic operation: crossover

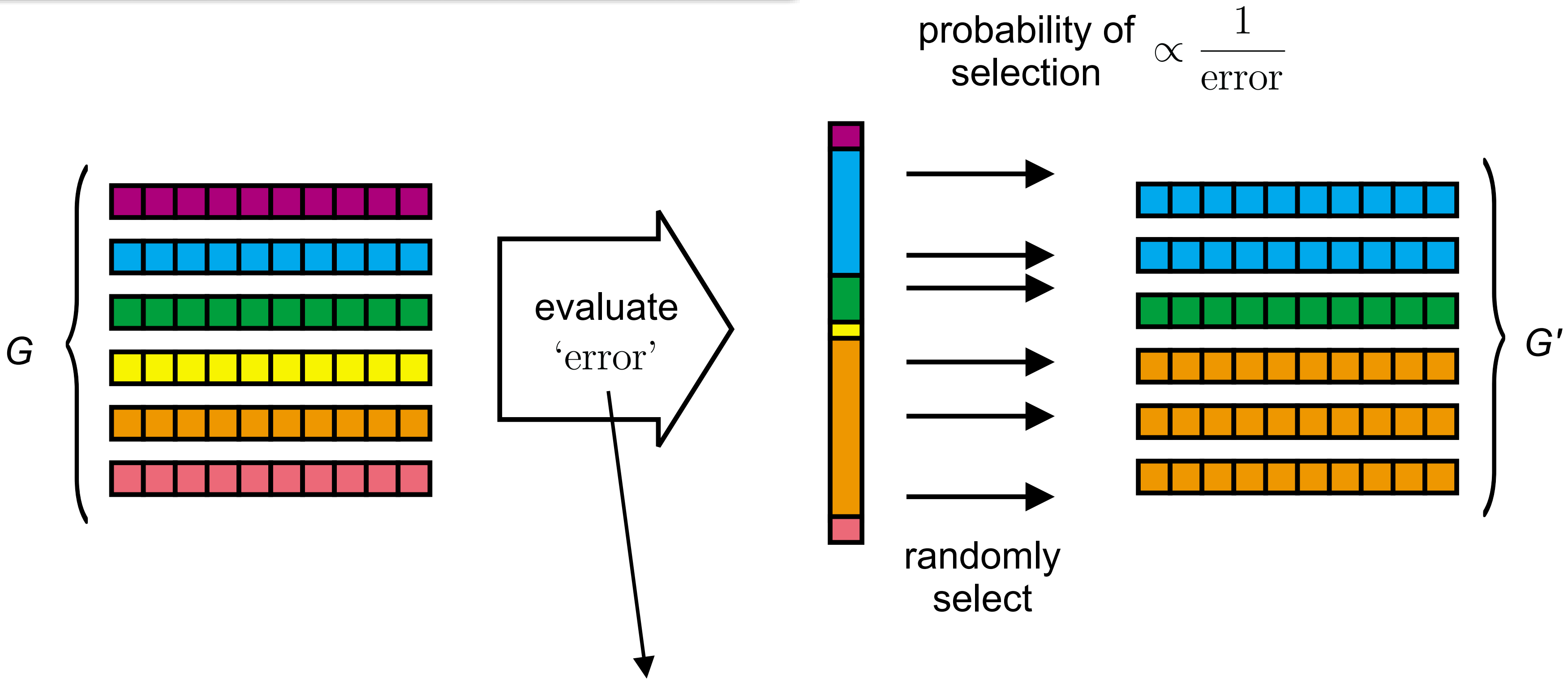


Basic operation: mutation





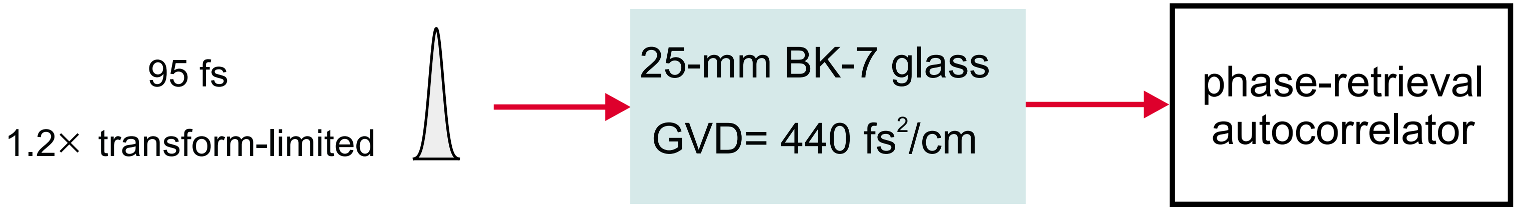
Basic operation: selection

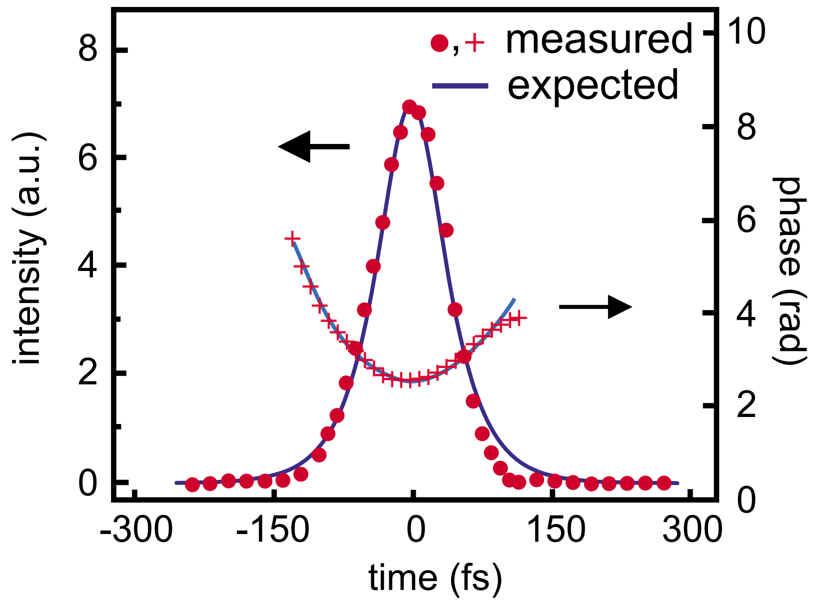


$$E(t) \;\begin{cases} I(t) = E^*(t)E(t) \xrightarrow{\mathcal{F}} \tilde{I}(\omega) \\ U(t) = E(t)E(t) \xrightarrow{\mathcal{F}} \tilde{U}(\omega) \end{cases}$$

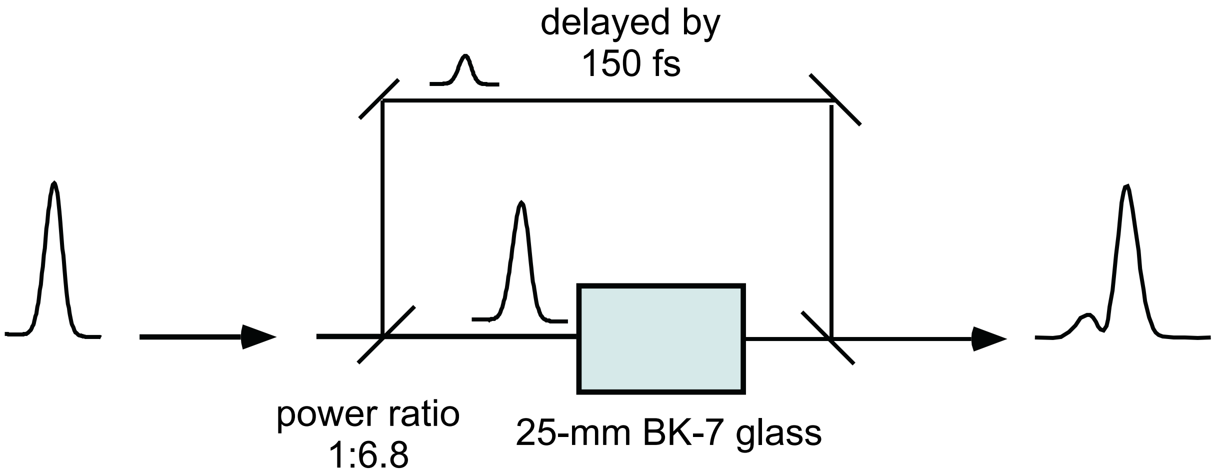
$\text{error} = \sqrt{Z_I^2 + Z_U^2}$, where $Z_I^2 = \dfrac{\sum(|\tilde{I}(\omega)|^2 - |\tilde{I}(\omega)|_{\mathrm{M}}^2)^2}{\sum|\tilde{I}(\omega)_{\mathrm{M}}|^4}$ and $Z_U^2 = \dfrac{\sum(|\tilde{U}(\omega)|^2 - |\tilde{U}(\omega)|_{\mathrm{M}}^2)^2}{\sum|\tilde{U}(\omega)_{\mathrm{M}}|^4}$.

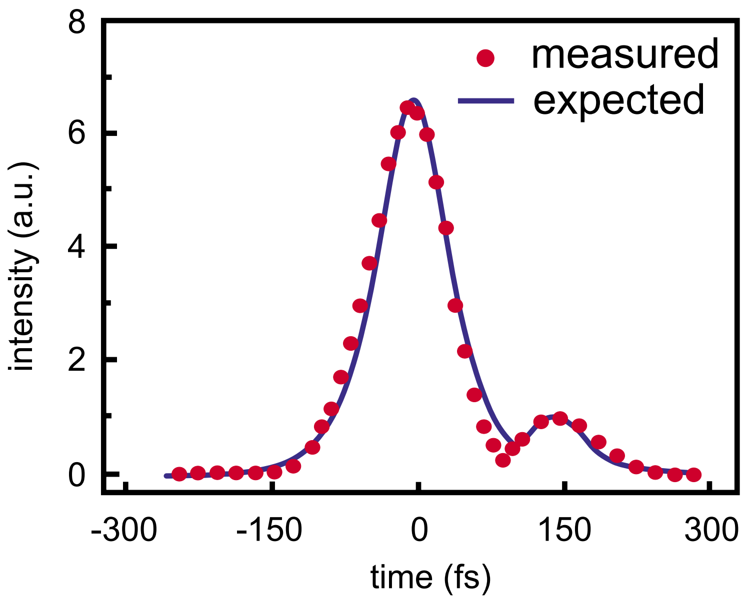
Demonstration 1: chirped pulses





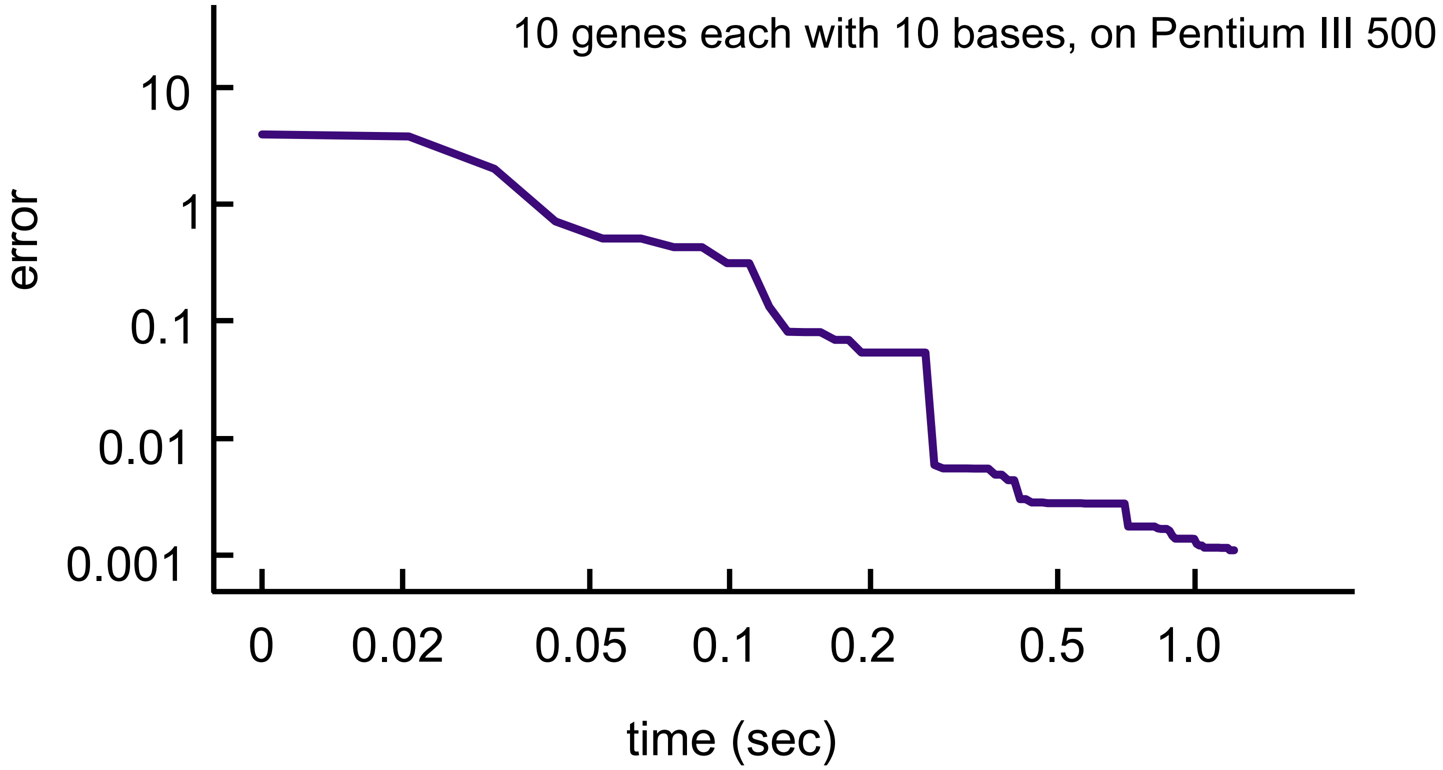
Demonstration 2: double-peak pulse



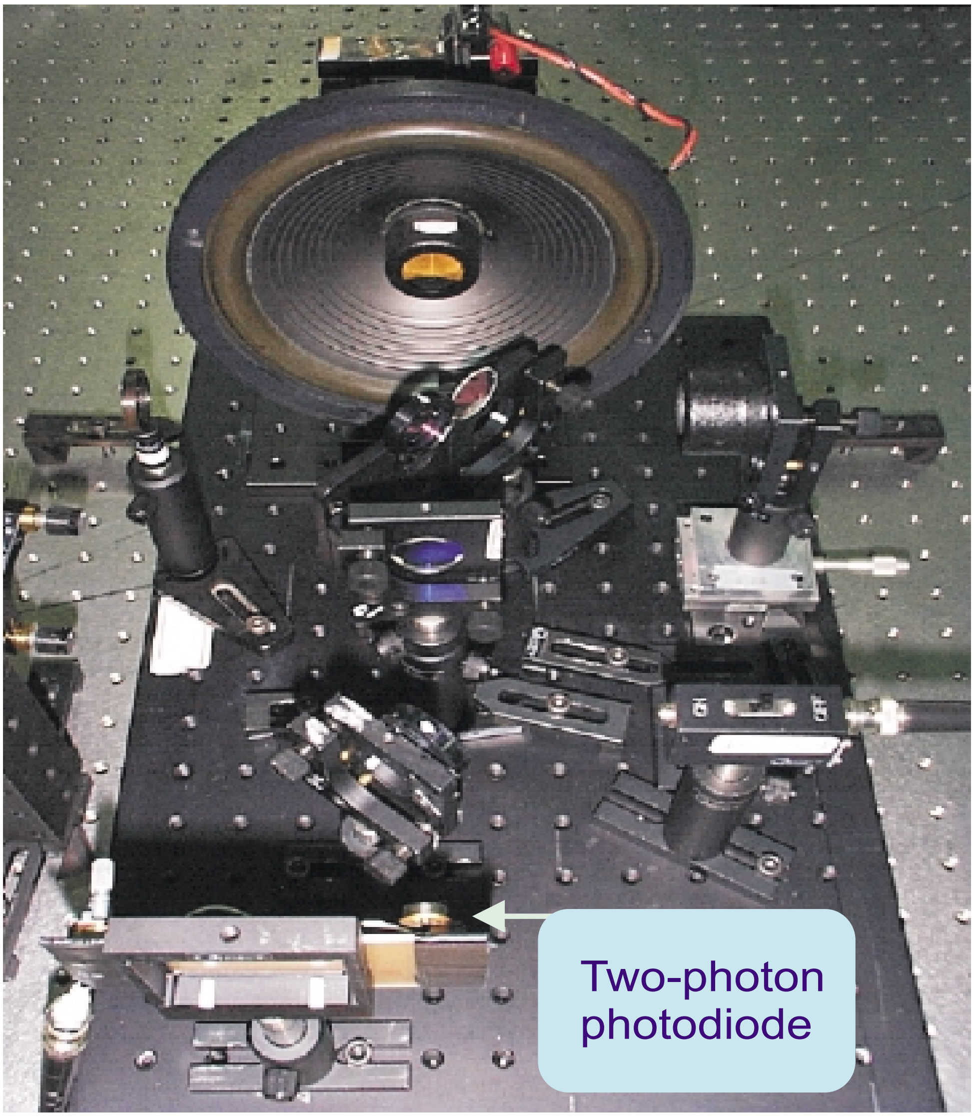


intensity profile of a double-peak pulse

Converging rate in phase retrieval with genetic algorithm



Semiconductor Phase-Retrieval Autocorrelator



45cm*30cm*30cm

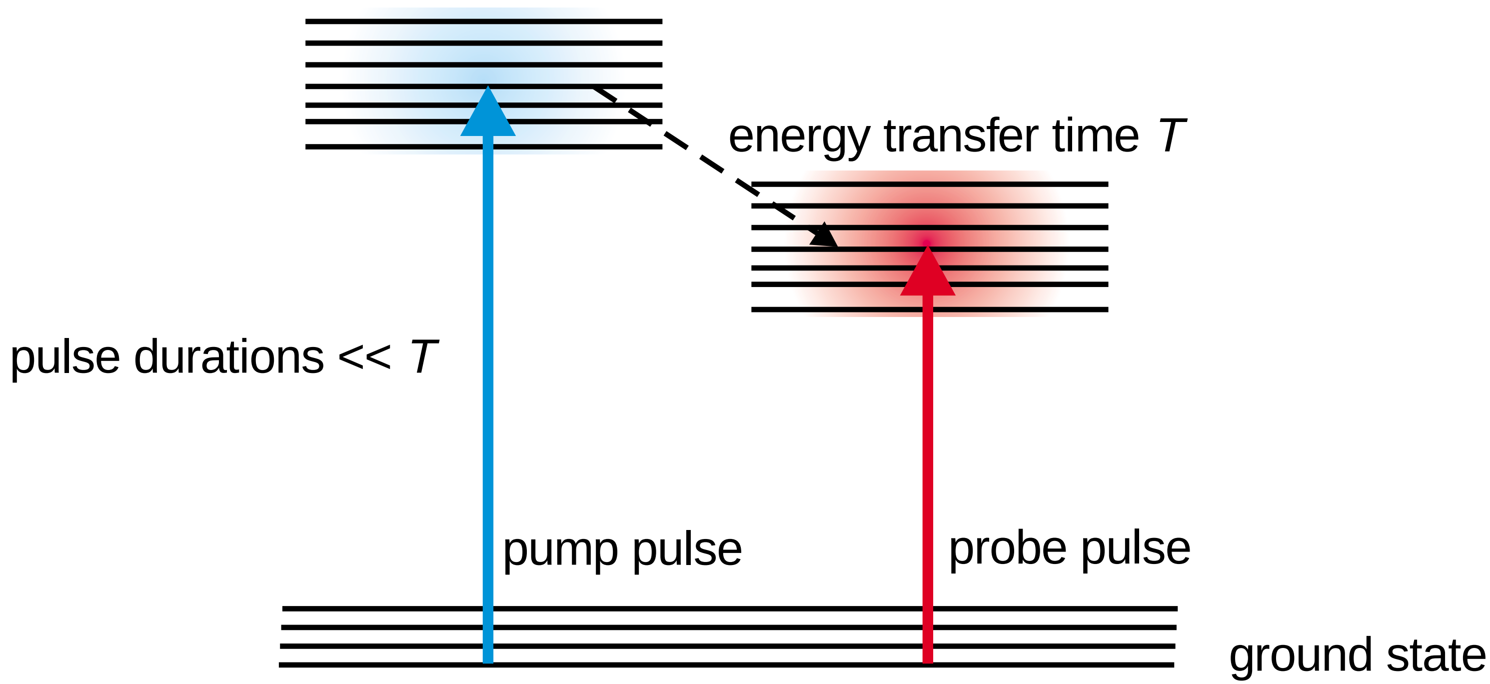
Potential applications

1. ultrafast spectroscopy

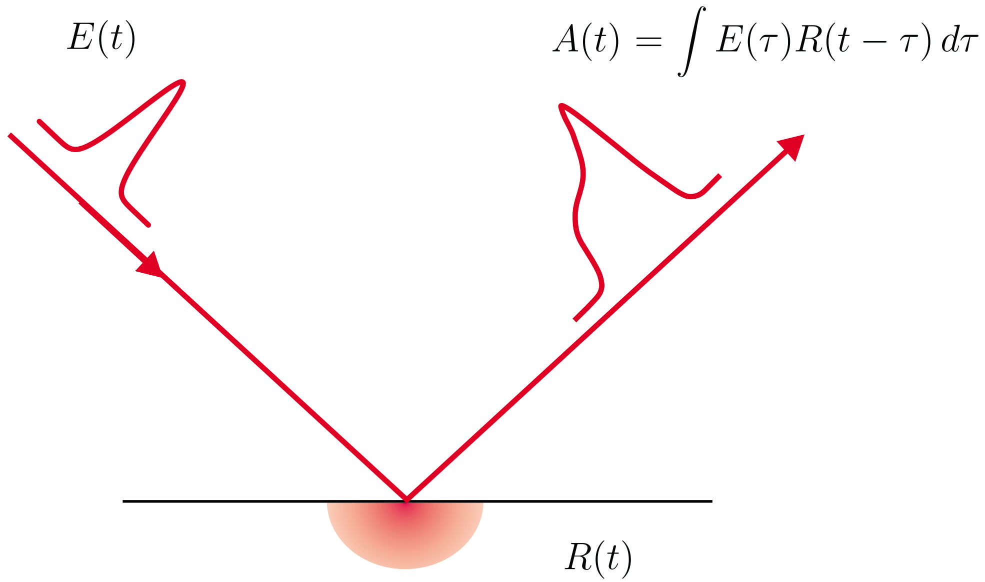
2. accelerator beam diagnosis

Ultrafast pump-probe experiments

transient absorption experiment

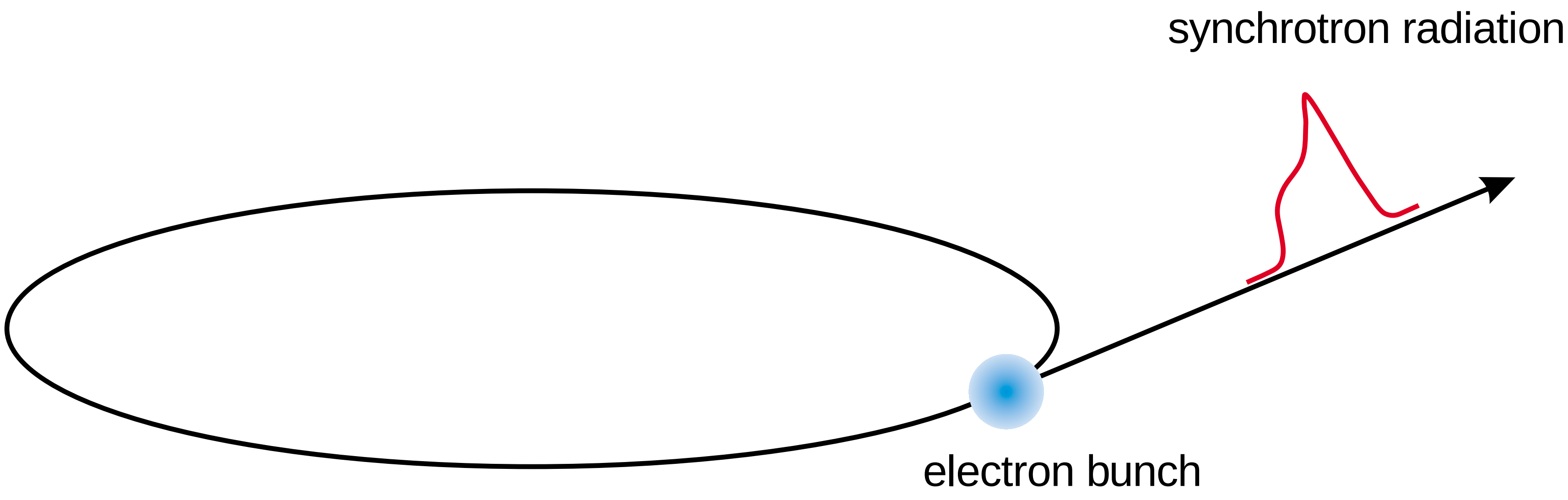


Avoiding excessive excitation bandwidth



It is possible to measure the material response with pulse duration of the same time scale, thereby avoiding excessive excitation bandwidth.

Beam diagnosis



Summary

- Slow nonlinear detectors can measure fast signals, without nonlinear wave mixing.
- From nonlinear interference, complete waveform can be reconstructed by the genetic algorithm.
- The technique is demonstrated with ultrafast optics, and can be used in other fields.